Collisions of Rare Earth Nuclei - a New Reaction Route for Synthesis of Super Heavy Nuclei

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Abstract

Theories have predicted an island of stability in the super heavy mass region with half lives ranging from a few seconds to a few thousands of years. Extensive efforts are being made experimentally to reach these nuclei in the region of Z = 110 and above with suitable combinations of proton and neutron numbers. However, the cross sections for production of these nuclei are seen to be in the range of a few pico barns or less, and pose great experimental challenges. We show in the present note that great advantages can be obtained by carrying out heavy ion reactions with suitable combinations of projectile and target nuclei in the rare earth region, that will lead to compound systems with very small excitation energy, and with better neutron/proton ratio for larger stability.

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I. INTRODUCTION

An island of superheavy nuclei, with half lives ranging from a few seconds to a few thousands of years has been predicted by calculations based on macroscopic-microscopic theories [1–3]. The large stability arises due to strong shell effects in the range of proton numbers (Z = 114 - 126) and neutron numbers (N = 170 - 188), which in turn gives rise to large fission barriers (∼5 - 8 MeV) in this mass region. There have been extensive efforts experimentally to synthesize superheavy nuclei through heavy ion reactions with suitable choice of projectile and target nuclei. However, the compound nuclei are formed at large excitation energies (a few tens of MeV), and due to washing out of shell effects with excitation energy, the production crosssections are usually quite low (in the range of pico barns or less) for compound nuclei with $Z = 110$ and above. Nevertheless, nuclei with Z up to 118 have been synthesized in laboratory by various experiments so far [4–6]. The two main routes followed are: 'hot fusion' with actinide target nuclei and asymmetric reaction channels (Dubna, Berkeley route) [7] and 'cold fusion' with Pb, Bi target nuclei with more symmetric reaction channels (GSI route) [4]. Another basic problem in these experiments is that the compound nucleus (CN) formed has much less neutron numbers as compared to that needed for the extra stability. Theoretically, there have been many recent attempts to understand the reaction mechanism leading to the formation of the superheavy nuclei [8–10].

One of the main reasons for poor success of the experiments is that the reaction $|Q|$-value is much lower than (for hot fusion), or similar to (for cold fusion) the Coulomb barrier of the target/ projectile. Hence, at beam energies just above Coulomb barrier, the CN is formed with high excitation energy which is already larger than the neutron emission threshold (∼ 7-8 MeV). For example, for ^{48}Ca + ^{249}Cf [(Z, A)CN = (118, 297)], Q= -174.48 MeV, V_{Coul} = 205.4 MeV and for ^{76}Ge + ^{208}Pb [(Z, A) CN = (114,284)], Q= -260.25 MeV, V_{Coul} = 272.1 MeV. Such is the case for other target / projectile combinations for similar reactions in which $V_{\mathrm{Coul}} > |Q|$ [11].

II. COLLISIONS USING RARE EARTH NUCLEI

The main considerations in selecting a reaction channel for producing super heavy nuclei are the following:

1. Large fusion cross section of projectile and target nuclei.

2. Low excitation energy of CN for optimum survival probability.

3. Proper neutron / proton ratio for better stability.

4. Intense beam intensity and target concentration for good yield.

As mentioned above, the cross-sections for SHE production have been found to be in the range of only a few pico barns or less in the experiments carried out so far. Recent reviews by W. Greiner [1] and others [12] have emphasized more on RIB routes and rare beams for producing $Z_{\mathrm{CN}} \geq 120$. In order to have better survival probability, radioactive neutron rich beams (^{96}Sr, ^{132}Sn) are being suggested to reach a more suitable neutron/ proton combination, which have severe limitation on beam intensity.

We give below in Table I some relevant data for the new reaction routes using rare earth nuclei fusion channels that are being suggested in this note. In addition to the reactions shown in the Table I, many more fusion reaction channels are feasible using other different rare-earth target/ projectile combinations. The advantages that these reactions offer are:

1. $V_{\mathrm{Coul}} < |Q|$ value.

2. Large g.s deformations of both target and projectile nuclei to give higher enhancement in near barrier fusion by channel coupling and lowering of fusion barrier, B_{fus}.

3. Good n/p ratios.

4. Stable beams for large beam intensity.

5. Large elemental abundances of rare earth elements.

6. large center of mass velocity for better collection of CN residues in forward direction.

7. Low neutron background at optimum low bombarding energy.

TABLE I: Relevant data for the new reaction routes using the rare earth nuclei.

Projectile/Target Z_{CN} A_{CN}	g.s. deformations Projectile/Target	Q- Value (MeV)	V_{Coul} (MeV)	S_n (MeV)
^{160}Gd + ^{154}Sm (126,314)	0.28 / 0.27	-412.2	396.2	7.3
^{154}Sm + ^{150}Nd (122, 304)	0.27 / 0.24	-377.5	373.9	7.1
^{150}Nd + ^{150}Nd (120, 300)	0.24 / 0.24	-361.5	362.6	7.2
^{154}Sm + ^{154}Sm (124, 308)	0.27 / 0.27	-394.9	385.5	7.1

For example, in case of ^{160}Gd + ^{154}Sm reaction, the CN is (126, 314) where V_{Coul} is 16 MeV lower than the energy required ($|Q|$-value) for initiating the reaction. With optimum bombarding energy, the CN can be produced in relatively low excitation energy region. N/Z ratio increases with each α-particle emission. Even after 6 α particles are emitted, the residual nucleus reached is (114, 290) with a N/Z ratio of 1.54.

However, it is now required to calculate the fusion/survival probability of the above rare earth reaction channels. One may expect that due to large $Z_P Z_T$ product there may be fusion hindrance. There is, however, no clear cut understanding of the fusion hindrance for deformed nuclei (except the extra push effects suggested by W. Swiatecki [13, 14]). There are some calculations reported in literature, where only target deformation is considered [15]. We give below some discussion on the basic method to have approximate estimates for the formation cross section of the super heavy nuclei using rare earth nuclear collisions.

III. THEORETICAL ESTIMATES

In case of heavy colliding systems typically used for super heavy mass region, overcoming the Coulomb barrier is not enough to form the super heavy compound nucleus. There are two avenues for estimating the compound nuclear formation cross section for heavy colliding nuclei similar to the ones discussed in the present article. These are: (i) extra-extra push

model [13, 14] and (ii) fusion by diffusion model [9]. According to the extra-extra-push model, an extra energy ('extra-extra-push') with respect to the Coulomb barrier is needed to land inside the unconditional saddle point which guard the colliding system against the re-separation before forming the compound nucleus. The 'extra-extra-push' energy increases rapidly with effective fissility. In the case of the present reactions where deformed projectile and target nuclei are considered, a large amount of 'extra-extra-push' energy is available ($\sim$ 100 MeV) at very low excitation energy ($<$ 8 MeV) for certain orientations of the colliding nuclei. At this juncture, a complete understanding of the entrance channel barrier distributions for these kind of heavy deformed nuclei with inclusion of dynamical effects is not easily calculable.

On the other hand, the fusion by diffusion (FBD) model has been quite successful in reproducing the measured excitation function of the super heavy element synthesis [9]. In the FBD model, for each value of the entrance channel angular momentum, the partial evaporation residue cross section $\sigma_{ER}(\ell)$ for production of a given final nucleus in its ground state is factorized as the product of the partial sticking cross-section $\sigma_{stick}(\ell)$, the diffusion probability $P_{\text{Diffus}}(\ell)$, and the survival probability $P_{surv}(\ell)$ [8] :

$$\sigma_{ER} = \sum_{\ell=0}^{\infty} \sigma_{stick}(\ell) P_{\text{Diffus}}(\ell) P_{surv}(\ell) \tag{1}$$

According to the partial wave analysis, $\sigma_{stick}(\ell)$=$\pi\lambda\!\!\!^{-2}(2\ell+1)T(\ell)$, where $T(\ell)$ is the capture transmission coefficient for the partial wave ℓ, and $\lambda\!\!\!^{-}$ is the reduced wavelength, $\lambda\!\!\!^{-2} = \hbar^2/2\mu E_{\text{c.m.}}$, where μ is the reduced mass of the colliding system. The capture transmission coefficients $T(\ell)$ are calculated in a simple sharp cutoff approximation: $T(\ell) = 1$ for $\ell \leq \ell_{\max}$, and $T(\ell) = 0$ for $\ell > \ell_{\max}$. In the above consideration, the Eq. (1) becomes;

$$\sigma_{ER} = \frac{\pi\hbar^2}{2\mu E_{\text{c.m.}}} \sum_{\ell=0}^{\ell_{\max}} (2\ell+1) P_{\text{Diffus}}(\ell) P_{surv}(\ell) \tag{2}$$

By replacing the summation in above equation by an integral, one obtains the sticking cross section as:

$$\sigma_{stick} = \frac{\pi\hbar^2}{2\mu E_{\text{c.m.}}} \sum_{\ell=0}^{\ell_{\max}} (2\ell+1) = \frac{\pi\hbar^2}{2\mu E_{\text{c.m.}}} (\ell_{\max}+1)^2 \tag{3}$$

$\ell_{\max}$ is determined by the "diffused barrier formula" based on assumption of Gaussian distribution of the barriers around a mean value B_0 (see Ref. [8] for details). The sticking

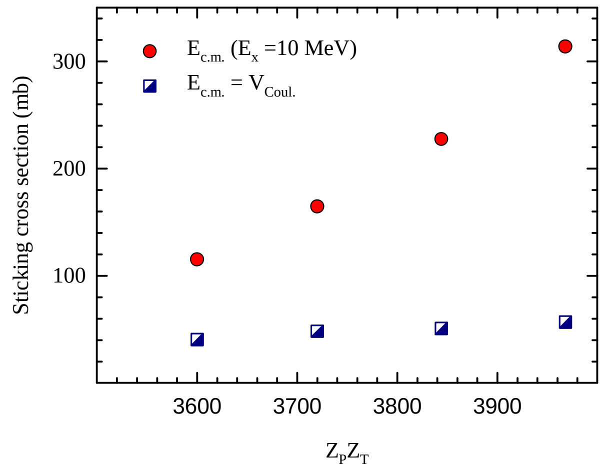

FIG. 1: Sticking cross section at two different $E_{c.m.}$ values as a function of $Z_P Z_T$ for the reactions discussed in the present work. Solid circles are for $E_{c.m.}$ values for which E_X =10 MeV and squares are for $E_{c.m.} = V_{\rm Coul}$.

cross sections determined for the present reactions are shown in the Fig. 1 as a function of $Z_P Z_T$.

In the FBD model, the probability ($P_{\rm Diffus}$) that the system injected at a point s_{inj} on the outside of the saddle point achieves fusion is calculated using the diffusion process over a parabolic barrier [9]. If L stands for the total length of dinuclear shape, the parameter s is defined as $s = L - 2(R_1 + R_2)$. In the entrance channel of two approaching nuclei $s = 0$ would correspond to contact of half density contours. The diffusion probability $P_{\rm Diffus}$ is then given by [8, 9]:

$$P_{\rm Diffus} = \frac{1}{2}\left(1 - erf\sqrt{H/T}\right) \tag{4}$$

where H is barrier height opposing fusion along the asymmetric fission valley, as seen from the injection point and T is the temperature of the fusing system. The diffusion probability as a function of barrier height, H at different T values is shown in Fig. 2. It is seen from Fig. 2 that the diffusion probability decreases very rapidly (depending on T) with increasing barrier height H. At a given H, $P_{\rm Diffus}$ is larger for higher temperature.

The macroscopic deformation energies are calculated as a function of the parameter s using the improved version of algebraic equations [8]. In order to estimate the barrier height, H, value of the parameter s at the injection point (s_{inj}) is the crucial parameter. In the FBD model this parameter s_{inj} is a free parameter which is adjusted to reproduce the measured

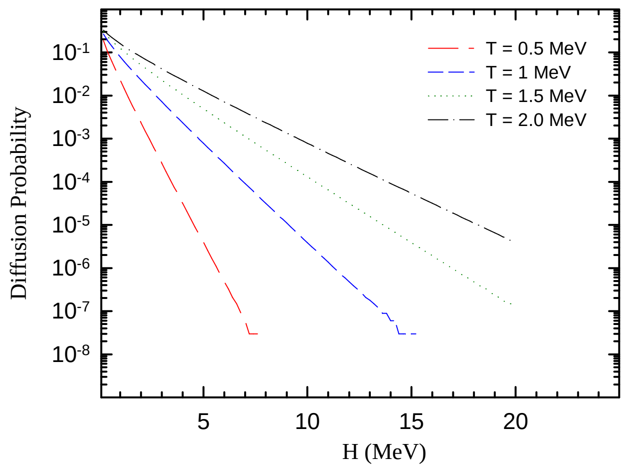

FIG. 2: Diffusion probability as a function of barrier height, H opposing fusion along the asymmetric fission valley, as seen from the injection point. Different lines correspond to the different mean values of temperatures (see text).

fusion cross section. In the work by Cap et. al. [8], s_{inj} is deduced for 27 cold fusion reactions including GSI, LBNL and RIKEN data. In that work, the s_{inj} values are plotted as a function of the excess of kinetic energy above the Coulomb barrier, $E_{c.m.} - B_0$, where B_0 is mean value of the Coulomb barriers (V_{Coul}). The overall trend of s_{inj} is of decreasing nature with increasing $E_{c.m.} - B_0$. Except the GSI data, all other data are scattered. For the purpose of present reactions, s_{inj} values (from Ref. [8]) for GSI data are considered and a least-square fit is obtained as shown in the Fig. 3. In Fig. 3, the straight line corresponds to the least-square linear fit;

$$s_{\mathrm{inj}} = 1.5985 - 0.23587(E_{c.m.} - B_0)\mathrm{fm/MeV} \tag{5}$$

Since present projectile-target nuclei are deformed ones, the fusion barrier distribution is expected to be quite broad [16]. Even at $E_X < 8$ MeV, a large fraction of the barrier distribution will have $(E_{c.m.} - B_0) > 30$ MeV, which will lead to s_{inj} ∼-5 fm as reflected from Fig. 3. For the present reactions, the barrier height, H is calculated at s_{inj} <=-5, -4, and -3 fm using the algebraic equations of macroscopic energies from Ref. [8] as shown in Fig. 4. It is seen from Fig. 4 that H values increase with $Z_P Z_T$ and they are lower for smaller value of s_{inj}. At s_{inj} =-4 fm, H values are around 5.5±1.5 MeV for all four reactions considered in the present work (see Table I). In the estimation of the diffusion probability

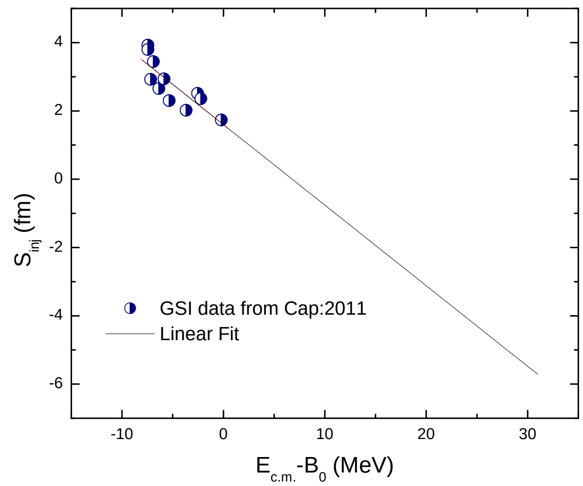

FIG. 3: The injection parameter(s_{inj}) as a function of $E_{c.m.} - B_0$ taken from Ref. A least square linear fit, $s_{\rm inj} = 1.5985 - 0.23587(E_{c.m.} - B_0)$ fm/MeV, is shown by the solid line.

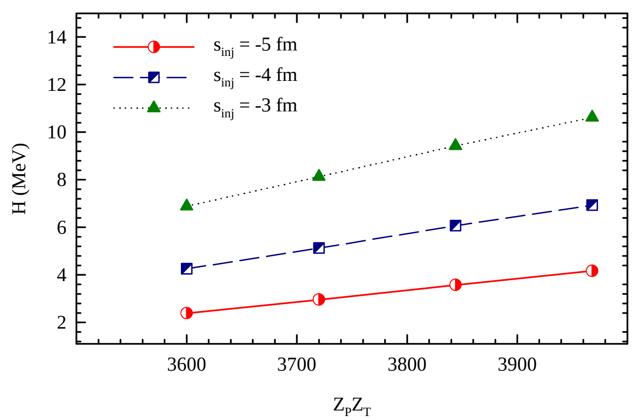

FIG. 4: The barrier height (H) as a function of $Z_P Z_T$ of the present reactions at various values of injection parameter(s_{inj})

using Eq. 4, the parameters H and T are crucial. At the excitation energy E_X <8 MeV, the temperature T is expected to be <1.0 MeV but definitely >0.5 MeV. Fig. 2 indicates that at $H \sim 5$ MeV the diffusion probability will be in between of 10^{-6} and 10^{-3}. Using Eq. 1 and Fig. 1 it appears that for the present reaction, lower limit of $\sigma_{stick} \times P_{\rm Diffus}$ is $\sim 10^{-7}$ barn. Present reactions using the rare earth nuclei offers a gain factor of the order of $\sim 10^4$ for $\sigma_{stick} \times P_{\rm Diffus}$ over the reactions of cold fusion, as can be seen from Fig.2 of Ref. [9].

As far as survival probability (P_{surv}) is concerned, for the present reactions it will be

larger than cold as well as hot fusion reactions due to following reasons: (i) initial excitation energies can be tuned to be very small (∼8 MeV). Therefore, shell effects are expected to be more prominent and (ii) good n/p ratios required for the stability of the super heavy elements. Even if we consider the same survival probability as of the cold fusion, viz. 10^{-4}, the final cross section for the synthesis of super heavy nuclei having $Z \geq 120$ is arrived to be $\sim 10^{-11}$ barn, which is significantly (10^4) larger than the cold fusion reactions. Present work invites more detailed theoretical calculations and definitely worth to be considered for experimental investigations. It is also necessary to carryout full microscopic calculations to understand the fusion mechanism for these heavy systems.

IV. SUMMARY

In the present work, we have made a case for the first time for the use of rare earth projectile and target nuclei to produce super heavy nuclei in the range of Z ∼116 and above. The advantages offered by these near symmetric collisions have been outlined. The cross sections for production of the super heavy nuclei in these collisions have been estimated within the framework of the fusion by diffusion model and are seen to be sufficiently large compared to other reaction routes considered so far. It is, however, necessary to carry out experiments to explore these novel possibilities of using rare earth nuclei for production of super heavy nuclei.

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